A PERFORMANCE EVALUATION OF INTERNAL LININGS FOR MUNICIPAL PIPE

100% SOLIDS POLYURETHANE

CERAMIC EPOXY

POLYETHYLENE

Shiwei Guan, Ph.D.
Chief Chemist

and

Howard Kennedy, B.Sc., MBA
Business Development Manager

Madison Chemical Industries Inc.
490 McGeachie Drive
Milton, Ontario, Canada L9T 3Y5
(905)878-8863 (Phone)   (905)878-1449 (Fax)

December, 1995

ABSTRACT

A complete evaluation program was designed to review the various types of lining systems that are presently available in North America for municipal pipeline internal coating application. These systems included 100% solids polyurethanes, ceramic epoxies, and polyethylenes used for the internal protection of potable water and wastewater mains. Key performance properties of the lining systems were reviewed and tested, together with handling and safety characteristics,. The behavior of the two 100% solids polyurethanes was excellent not only in all tests but in their handling and safety characteristics as well. Polyethylenes were good in many tests such as impact resistance and abrasion resistance, but performed poorly in the cathodic disbondment test. Even though the ceramic epoxy showed relatively good chemical resistance and undercutting resistance, its poor adhesion, low impact resistance and brittleness raised concerns about its ability to provide long term corrosion protection in aggressive sewer applications.

A PERFORMANCE EVALUATION OF INTERNAL LININGS FOR MUNICIPAL PIPE

100% SOLIDS POLYURETHANE

CERAMIC EPOXY

POLYETHYLENE LININGS

Shiwei Guan, Ph.D.
Chief Chemist
and
Howard Kennedy, B.Sc., MBA
Business Development Manager

Madison Chemical Industries Inc.
490 McGeachie Drive, Milton, Ontario, Canada L9T 3Y5
(905)878-8863 (Phone) (905)878-1449 (Fax)

ABSTRACT

A complete evaluation program was designed to review the various types of lining systems that are presently available in North America for municipal pipeline internal coating application. These systems included 100% solids polyurethanes, ceramic epoxies, and polyethylenes used for the internal protection of potable water and wastewater mains. Key performance properties of the lining systems were reviewed and tested, together with handling and safety characteristics,. The behavior of the two 100% solids polyurethanes was excellent not only in all tests but in their handling and safety characteristics as well. Polyethylenes were good in many tests such as impact resistance and abrasion resistance, but performed poorly in the cathodic disbondment test. Even though the ceramic epoxy showed relatively good chemical resistance and undercutting resistance, its poor adhesion, low impact resistance and brittleness raised concerns about its ability to provide long term corrosion protection in aggressive sewer applications.

Keywords: 100% solids, polyurethane, ceramic epoxy, polyethylene, sewer, potable water, wastewater pipe lining

INTRODUCTION

Corrosion is considered to be the major reason for structure failures. The loss of the structure is serious enough in its self, but the unscheduled loss adds synergistically to operating expenses in the form of lost production or, worse, the loss of life and property from a corrosion-induced accident. In many instances, the most and perhaps the only effective measure that can be taken for corrosion control is to protect the structure with a coating. The coating acts as a barrier to prevent chemical compounds and/or corrosion current from contacting the structural material. Many variables are involved in achieving a desired life of the protection by a coating system such as substrate, environment, surface preparation, coating properties, as well as application method. Coating selection is recognized as a difficult, yet important process.

Corrosion control by coatings has progressed to a scientific level. This allows engineers and utilities to make reliable predictions and selections regarding specific corrosive conditions and coatings and to use a selected coating to prevent corrosion. Results of various performance laboratory tests on different coating systems are playing a major role in this exercise. Such performance results form the basis in establishing their correlation with field performance, predicting the long term life expectancy of the protection.

100% solids polyurethanes, ceramic epoxies, and polyethylenes are three lining systems that have been widely used in protecting structures made of steel, ductile iron, and concrete from internal corrosion, particularly in potable water and tough sewer pipe applications. 100% solids polyurethanes and polyethylenes are suitable for both potable water and waster water applications, while ceramic epoxies are being used for waste water service only. The progressive evolution in the choice of the above three coating systems for a specific application is usually based on one hand, on the accumulation of the experience acquired in the field, and, on the other hand, on knowledge of the products available. This information can be obtained first from data furnished by product suppliers. Many end users, however, often find that it is impossible to rely solely on individual supplier’s data. This is mainly due to: 1) results of a proprietary test being done by one supplier may not be available from other product suppliers; 2) different test methods have been used; and 3) there are many varieties of tests giving results which cannot easily be compared.

During the course of the past five years, a complete evaluation program has been conducted for Madison by three independent laboratories which specialize in coating tests and by a major pipe manufacturer. The purpose of this paper is to sum up these tests on polyurethanes, ceramic epoxies and polyethylenes in order to establish the main conclusions applicable to the choice of these coating products for pipe internal lining applications.

METHODOLOGY OF TEST PROGRAM

The evaluation program encompassed to the testing of four lining materials:

- a 100% solids, two component, instant setting, petroleum tar extended polyurethane coating developed specifically for wastewater service (identified below as “PUR WW”);
- a 100% solids, solvent free, two component, instant setting, pure polyurethane coating used for all kinds of service including chemical immersion, potable water and wastewater (identified below as “PUR PW”);
- a ceramic epoxy coating, i.e. coal tar epoxy filled with “ceramic” fly ash fillers; and
- a low density polyethylene material.

The initial stage in the evaluation of the lining material was a review of the handling and safety characteristics of the material. Information was compared from technical data sheets and MSDS’s provided by the coating suppliers.

The second stage was the actual testing of the lining materials. Samples of the two polyurethane materials were provided by the actual coating supplier. Samples of plant-applied ceramic epoxy and polyethylene materials were supplied by a pipe manufacturer, applied according to the application procedures from the coating suppliers. This ensured that the application was indicative of the supplier’s normal coating procedures and that the applied samples were truly representative of the product being tested.

The following tests were conducted:

- Adhesion (ASTM D4541)
- Abrasion resistance (ASTM D4060)
- Cathodic disbondment (ASTM G95)
- Chemical resistance (ASTM D714, D543)
- Flexibility (ASTM D522)
- Hardness (ASTM D2240)
- Impact resistance (ASTM D2794)
- Permeability (ASTM E96)
- Salt spray (ASTM B117)
- Weathering resistance (ASTM G53)

The above tests are listed in alphabetic order and not in any special order of importance since many of them are interdependent.

MATERIALS AND THEIR HANDLING AND SAFETY CHARACTERISTICS

Handling characteristics of the 100% solids polyurethanes and ceramic epoxy systems include solids content, initial setting time, cure to handle/quality control test time, cure to service time, and application temperature. These characteristics were reviewed and summarized in Table 1.

100% solids polyurethanes are becoming more and more of interest to users because of environmental regulations. By definition, the term “100%” means the coating system does not use any solvent to dissolve, carry or thin down any of the coating resins. It is not an indication of viscosity or filler content. In fact, neither PUR WW nor PUR PW contain fillers. Furthermore, the coating solutions normally in a liquid state, will convert, 100% by volume, to a solid film after application. Coating systems that are classified as 100% solids may contain a small amount of solvent or VOC’s (less than 5%) that acts as a dispersing agent, a stabilizer or as a carrier for pigments, catalysts or other additives.

100% solids polyurethanes containing pure isocyanate and polyol resins only (e.g. PUR PW) may be suitable for both potable water and waste water applications. However, petroleum tar or coal tar extended 100% polyurethanes are used for waste water service only. Coal tars have been proved to cause human cancers, whereas petroleum tars only contain trace amount of ingredients which may have the potential of causing skin cancer only by long term direct skin contact[2]. The petroleum tar-extended 100% polyurethane coating used in this study (PUR WW) is inert when cured, and can be disposed by common landfill as a non-hazardous material. Both PUR WW and PUR PW have the handling characteristics of true cold temperature curing and instant setting[3] as indicated in Table 1.

Table 1 Handling Characteristics of 100% Polyurethanes and Ceramic Epoxy

Characteristic	PUR WW	PUR PW	Ceramic Epoxy
Solids content	98 ± 2%	100%	90%
Initial setting time (70°F)	10-15 minutes	5-8 minutes	4-6 hours
Initial setting time (32°F)	20-25 minutes	10-12 minutes	Will not set
Cure to handle/test (70°F)	1 hour	15-20 minutes	3-4 days
Cure to handle/test (32°F)	2 hours	30-45 minutes	Will not set
Cure to service (70°F)	48 hours	24 hours	7-10 days
Cure to service (32°F)	100 hours	48 hours	Will not set
Application temperature	-40°F to 150°F	-40°F to 150°F	> 40°F

Coal tar epoxies typically contain about 40% epoxy resins, 30% tar, and 25-30% solvents. In the ceramic epoxy used in this study, this information was not published by the supplier. However, it was estimated that the solids content was increased to approximately to 90% by replacing some solvents with “ceramic” fly ash fillers in this amine-cured system. According to the supplier, at least 20% of the volume of the lining contains the “ceramic” fillers[4]. Fly ash is a waste by-product of the burning of coal in power stations and contains several metallic oxides, hence has the expression “ceramic” fillers. The large loading of both coal tar and “ceramic” fillers reduces significantly the cost of the material. Because of the presence of coal tar and the fillers, the ceramic epoxy is a plant-applied coating for sewer application only. Slow setting and poor cold temperature curing capability are two major drawbacks of all types of epoxies including the ceramic epoxy system.

Polyethylene is used as a coating by melting it onto the inside of a pipe. The pipe is filled with beads and heated to a temperature above the melting point of polyethylene. Polyethylene is a thermoplastic whereas the other products reviewed in this study are thermosetting polymers. The handling characteristics above are not applied to polyethylene because that the material must be melted into place at high temperatures.

Table 2 Safety characteristics of 100% polyurethanes, ceramic epoxy, and polyethylene

Characteristic	PUR WW	PUR PW	Ceramic Epoxy	Polyethylene
Contains coal tar	No	No	Yes	No
Contains amines	No	No	Yes	No
Contains monomeric isocyanate	No	No	No	No
VOC's	0.105 lbs/gallon	Zero	1 lbs/gallon	Zero
Flammable	No	No	Yes	No
Liquid product classified as "dangerous goods"	No	No	Yes	Not applicable
Disposal of cured overspray	Non hazardous	Non hazardous	Hazardous	Not applicable
"Early warning" feature	Yes	Yes	No	Not applicable
Suitability for potable water	No	Yes	No	Yes

Table 2 outlines safety characteristics of 100% polyurethanes, ceramic epoxy, and polyethylene. The two 100% solids polyurethanes used in this study use only a MDI type of polymeric isocyanate, which is not carcinogenic and its only problem is that may cause temporary irritation of the respiratory system, skin and eyes when over-exposed. Most applicators will know that they are being over exposed because they get runny noses, itchy eyes and irritated throats. Once the over-exposure is stopped, the allergic reactions end. These "early warning" discomforts are very effective ways to avoid over exposure. Over exposure to isocyanates can be controlled simply by wearing respirators, gloves and other protective clothing as per standard painting practices[5]. Such an "early warning" feature is not available for the ceramic epoxy system which contains amines, coal tar and other hazardous ingredients.

TESTING RESULTS AND DISCUSSIONS

Adhesion

The adhesion of a coating is generally considered to be a good indicator of its longevity. A generally accepted adhesion value for "adequate" corrosion protection is 1000 p.s.i. The greater a coating's adhesion to the substrate, the longer it will last.

Table 3 shows average values of the adhesion of the lining systems to steel and ductile iron (ASTM D4541). Samples are prepared using the best possible surface preparation according to specifications given by the coating supplier. Clearly, the 100% solids polyurethane materials showed the best adhesion compared with the other coating systems.

Table 3 Results of Adhesion Test (ASTM D4541)

	PUR WW	PUR PW	Ceramic Epoxy	Polyethylene
Steel	2000 p.s.i. (glue failure)	2200 p.s.i. (glue failure)	150 p.s.i.	700 p.s.i.
Ductile iron (DIP)	2601 p.s.i. (cohesive failure, no failure of adhesion to DIP)	3300 p.s.i. (cohesive failure, no failure of adhesion to DIP)	200 p.s.i.	800 p.s.i.

Abrasion Resistance

For sewer applications, the internal lining of a pipe must resist the continual flow of sewage, sometimes with abrasive materials in the liquid. The Taber abrasion test (ASTM D4060) rotates a sample of the coating, under a load pressure of the certain weight (1 kg), against a grinding wheel using a specified size of wheel (CS17) and a defined number of revolutions (1000 cycles). The samples were evaluated by measuring the change in mass before and after the abrasion. Test results are shown in Table 4. The lower the weight loss, the better the abrasion resistance of the coating. As is already recognized by the industry, the polyurethanes and polyethylene showed good abrasion resistance. Compared with conventional epoxies, the addition of "ceramic" filler did significantly improve the abrasion resistance of the epoxy system by 10 to 30%.

Table 4 Results of Abrasion Test (ASTM D4060)

	PUR WW	PUR PW	Ceramic Epoxy	Polyethylene
Weight loss	78 mg loss	52 mg loss	152 mg loss	12 mg loss

Cathodic Disbondment

This test is one measure of undercutting resistance of a coating. Experience in the oil and gas pipeline industry has clearly shown that coatings with better cathodic disbondment resistance (less disbondment), have better corrosion resistance and greater longevity.

The test was conducted per ASTM G95 at 73^{o}F±3^{o}F for 30 days using 3% NaCl and -1.5 Volts DC. Dry film thickness of all coating systems were set at 40 mils as per the supplier's recommendations for ductile iron pipe lining application. A 0.125 inch diameter hole (holiday) was drilled through the coating to expose the DIP substrate. After the test, the radial disbondment was measured in millimeters from the edge of the holiday to the point where the coating showed good adhesion. The results are shown in Table 5.

Table 5 Results of Cathodic Disbondment Test (ASTM G95)

	PUR WW	PUR PW	Ceramic Epoxy	Polyethylene
Disbondment	9.9 mm	8.0 mm	12.8 mm	Failure

There seems to be a common behavior that results of cathodic disbondment test are very inconsistent from one laboratory to another and form one type coating to another. This is because many variables are involved in the test and thus affect the results. The diameter of initial holiday for the cathodic disbondment test is one of these variables[6]. A larger diameter of the initial holiday normally tends to give better cathodic disbondment results. This behavior was also noted in this study. The disbondment of ceramic epoxy obtained in this study (initial diameter of the holiday = 0.125 inch) was very different from that provided by the coating's supplier. The coating's supplier used a 0.25 inch holiday for the test and obtained a 0.5 mm of disbondment after 30 day exposure. The mechanism of how the initial diameter of the holiday affects the disbondment of a coating is not yet known. However, a joint research project between the authors and the Corrosion Laboratory at the University of Alberta has been ongoing to fully understand the mechanisms of cathodic disbondment using micro-electrode technology to investigate the local electrochemical changes inside the electrolyte solution of the small holiday[6].

For polyethylene, there was no cathodic disbondment in the traditional sense on any samples tested. However, the polyethylene materials exhibited an unusual mode of failure. There were numerous blisters with open pin holes surrounded by calcareous deposits throughout the exposed (immersed) area on each of the three samples and microscopic examination revealed rust breakthrough at these sites.

Chemical Resistance

Two ASTM test methods were used in this study. The first one, ASTM D714, monitors the effect of a solution when the coating is applied to a metal coupon. The evaluation is completed by observing the panel for blisters after immersion. While this test provides a “true-life” condition, the end result is that the coating may really only be recommended as being suitable for the length of service that it was tested at. Table 6 summarizes the test results of the coating systems for up to 3500 hours. Results indicated that all these systems were quite resistant to common chemicals that were found in a septic sewer system.

Table 6 Results of Chemical Resistance Test (ASTM D714)

Solution	# of Hours	PUR WW	PUR PW	Ceramic Epoxy	Polyethylene
20% H_2SO_4, 70^{o}F	2400	passed	passed	passed	passed
20% H_2SO_4, 140^{o}F	2400	passed	passed	passed	passed
35% HCl, 70^{o}F	2400	passed	passed	passed	passed
Sat. NaOH, 70^{o}F	3500	passed	passed	passed	passed
Sat. NaOH, 140^{o}F	3500	passed	passed	passed	passed

Thibert[7] has reported her test results on 100% polyurethanes, ceramic epoxy, and polyethylene using a modified ASTM D714 method. The test involved soaking test panels in increasingly stronger solutions of sulfuric acid. The first test required a soak of 20% acid for 24 hours. The solution was increased 20% each additional 24 hours. Results showed that only 100% polyurethanes and polyethylenes were able to resistant to the sulfuric acid solution of up to 80%. Ceramic epoxy samples showed coating failure at such high acid concentrations.

Beyond blisters, the ASTM D714 test method does not allow for any evaluation of the change of physical properties of an actual coating film (e.g. weight gain or loss). In a past test, a coating that passed at 6 month immersion with ASTM D714, failed after 12 months of actual service. However, that particular coating failed ASTM D543 test. In ASTM D543 test method, free films of a coating are weighed and then immersed in a solution for at least 7 days. After the immersion time, they are dried and weighed again combined with evaluation of other properties (e.g. size change, general appearance, etc.). If the weight change beyond 7 days is minimal or there is no weight change or if the weight change is less than 3% over 30 days and if there are no significant size and appearance changes, the coating may be recommended for constant and continual immersion service for the solution. Over the past 20 years, this criterion has been found to be extremely reliable. In this study, free films of the two 100% solids polyurethanes (PUR WW and PW) were tested in the solutions listed in Table 6. Both of them passed the test. Free films of plant-applied ceramic epoxy and polyethylene coatings, however, were not available for the test and thus no comparisons were made. The ceramic epoxy is, in any event, too brittle to test as a free film; it snaps or shottens when handled.

Flexibility

This evaluation was designed to provide an indication of the ability of a coating to resist cracking, tearing, disbonding or any other mechanical damage as a result of field bending during pipeline construction. ASTM D522 test method was used. Only PUR WW, PW and polyethylene coated samples passed at 180^o over a 2” mandrill (Table 7). The ceramic epoxy samples were so brittle that they exhibited almost no flexibility.

Table 7 Results of Flexibility Test (ASTM D522)

	PUR WW	PUR PW	Ceramic Epoxy	Polyethylene
Flexibility over 2” mandrill	180^o	180^o	Failure	180^o

Hardness

This test method measures the ability of a coating to dissipate a dynamic load. All tests were conducted at a temperature of 70^{o}F.

Shore D hardness (ASTM D2240) was measured on the four coating systems (Table 8). Resistance between 55-80 was found. Hardnesses in this range (55-80) are commonly accepted as being suitable for internal lining applications.

Table 8 Results of Hardness Test (ASTM D2240)

	PUR WW	PUR PW	Ceramic Epoxy	Polyethylene
Hardness (Shore D)	65	80	80	55

Impact Resistance

This test provides a method for producing and measuring the effect of controlled impact damage on a coating surface. The test method used was ASTM D2794 using ductile iron pipe samples with a 40 mil lining. The equipment was the Gardner Impact Tester. Impact on the coated pipe surface was produced by dropping a known weight (4 lbs) down a slotted tube onto a spherical cup (a 5/8” ball), to produce a “point impact” on the surface of the coated pipe specimen. Initially the test specimen was impacted from 20 in-lbs and its effect on the coating was noted at the point where a holiday was detected by a wet sponge holiday tester. If the coating failed, the height was reduced for the next drop; if no holiday was found, the height was increased. No point on the coating surface was tested more than once. The procedure was repeated until a constant film failure value was obtained. Results of this test is shown in Table 9. A ceramic epoxy sample after the impact resistance test is also shown in Fig. 1. The mode of failure was a shattering of the coating.

Table 9 Results of Impact Resistance Test (ASTM D2794)

	PUR WW	PUR PW	Ceramic Epoxy	Polyethylene
Impact resistance	110 in-lbs	70 in-lbs	20 in-lbs	160 in-lbs

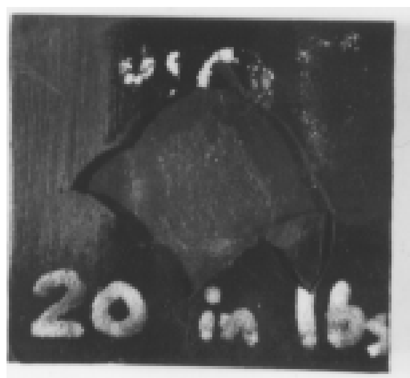

Fig.1 The ceramic epoxy sample exhibited poor impact resistance because of its brittleness

The impact resistance claimed by the manufacturer of the ceramic epoxy was much higher than the values obtained from commercial samples in this study. One reason for this discrepancy might be the tendency of the ceramic epoxy to become increasingly brittle over time and/or after exposure to elevated temperatures.

Permeability

Permeability is a measure of the ability of a water borne chemical or gas to penetrate the lining of the substrate. The lower the number in perms the better the lining will resist blistering and disbondment.

Procedure A of ASTM E96 test method was used to determine the permeance of the submitted coating samples after 30 days. In general, the results shown in Table 10 indicated the permeance of all the coating systems investigated were quite low, compared with other conventional coatings. The relatively higher permeance of the polyethylene materials was consistent with their results of the cathodic disbondment test described before as well as those of the salt spray test to be discussed below. It was also consistent with an early study found in the literature on water absorption of polyethylene coating systems.[8] During short term exposure (24 hours) to water, polyethylene systems demonstrated a higher resistance to water absorption than did polyurethanes and coal tar enamels. However, longer term exposure (12 months) showed a reversal of this trend.

Table 10 Results of Permeability Resistance Test (ASTM E96)

	PUR WW	PUR PW	Ceramic Epoxy	Polyethylene
Perms	0.0045	0.0020	0.0040	0.032

Salt Spray

The salt spray test is the conventional method of measuring undercutting resistance but the results are not as clear as the cathodic disbondment test. The test was conducted as per ASTM B117 with 1000 hours exposure. No undercutting of any consequence was observed with any of the materials investigated, nor was any blistering found when rated using ASTM D-714. All the systems showed similar total disbondment results from Scribe to those obtained from the cathodic disbondment test above (Table 11).

Table 11 Results of Salt Spray Test (ASTM D-714)

Materials	Rust breakthrough	Blistering	Disbondment from Scribe	Under film corrosion
PUR WW	0	0	11.0 mm	0
PUR PW	0	0	8.5 mm	0
Ceramic Epoxy	0	0	15.6 mm	0
Polyethylene	0	0	8.35 mm	2.25 mm

Practical experience has shown that polyethylene lining in ductile iron pipe has failed due to disbondment over an extended period of time (e.g. several years)[9]. The fact that under film corrosion was developed in the cathodic disbondment test and also salt spray test may be more indicative of future problems.

Weathering Resistance

Since coated pipe may be stored outdoors for long periods before burial, weathering tests are needed to evaluate the stability of coatings while stored outdoors. The results obtained should however, be rated only as indicating the general effect of weathering, primarily from ultra-violet degradation.

The test method was ASTM G53 using the QUV Accelerated Weathering Tester. After 4 month exposure, samples of all materials showed slightly color change with no cracking or checking. After 12 month exposure, however, ceramic epoxy samples showed the development of hairline cracks (Table 12).

Table 12 Results of Weathering Resistance Test (ASTM G53)

Exposure period	**PUR WW**	**PUR PW**	**Ceramic Epoxy**	**Polyethylene**
4 months	Slight color change, no cracking or checking	Slight color change, no cracking or checking	Slight color change, no cracking or checking	Slight color change, no cracking or checking
12 months	darken and chalking, no cracking or checking	darken and chalking, no cracking or checking	Chalking with hairline cracks	darken and chalking, no cracking or checking

The authors also had the opportunity to evaluate pipes that had been coated and left in the sun in the area of Atlanta, Georgia. After two and a half years, the ceramic epoxy had severely mud cracked. It was flaking off and was providing virtually no protection to the substrate (Figure 2). A pipe with 100% polyurethane and stored in the same yard for six years showed no degradation other than surface chalking (Figure 3).

Fig.2 Ceramic epoxy after 2.5 years out of doors in Atlanta, Georgia

Fig. 3 Polyurethane lining after 6 year exposure in the same yard

CONCLUSIONS

An evaluation program was designed to review the various types of lining systems that are presently available in North America for municipal pipeline internal coating applications. It is important to note that the objective was to provide an assessment of each generic group of linings and it was not intended to evaluate any specific system for the purpose of qualifying its use. Comparative tests are necessary to enable the end user to obtain as much information as possible concerning the pipe lining products on the market and thus to make their own best selection according to the laying and operating conditions.

The behavior of the two 100% solids polyurethanes was excellent not only in all tests but in their handling and safety characteristics as well. Polyethylenes were good in many tests such as impact resistance and abrasion resistance, but performed poorly in the cathodic disbondment test. Even though the ceramic epoxy showed relatively good chemical resistance and undercutting resistance, its poor adhesion, low impact resistance and brittleness raised concerns about its ability to provide long term corrosion protection in aggressive sewers applications.

REFERENCES

1. American Society for Testing and Materials (ASTM), "*Annual Book of ASTM Standards"*

2. The Occupational Health Program, McMaster University, "*Health Effects of Coal Tar products and Bitumens*", 1986

3. Shiwei Guan, "*Assuring Quality in Applying 100% Solids Polyurethanes*", JPCL, December, 1995

4. U.S. Pipe & Foundry Co., "*Ceramic Epoxy Lined Ductile Iron Pipe and Fittings for Force Hains and Gravity Sewer Lines*", 1995

5. American Industrial Hygiene Association, "*Toxicology, Industrial Hygiene and Medical Control of Polyurethanes and Related Materials*", 1983

6. Jingli Luo and Shiwei Guan, "*Study on Cathodic Disbondment Using Micro-electrode Technology*", Submitted for and accepted by the Annual Conference of the Canadian Institute of Mining and Metallurgy (CIM), 1996

7. Department of Metropolitan Service, King County, Seattle, Washington, "*Test Report on Pipe Lining Materials*", October 30, 1995

8. Coulson and D.G. Temple, "*Pipeline Coatings, Is It Really A Cover-up Story*?", In Proceeding of the NACE 1984 Corrosion Conference, 355/1-23, 1984

9. Shiwei Guan and Howard Kennedy*, "Test Report on Corropipe II Wasteliner*", Madison Chemical, December, 1994